NASA TECHNICAL TRANSLATION

NASA TT F-15,964

2.2 mm WAVELENGTH FREQUENCY CONVERTER

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(NASA-TT-F-15964) THE 2.2 mm WAVELENGTH FREQUENCY CONVERTER (Scientific Translation Service) 11 p HC $4.00

N74-34642

CSCL 09C

Unclas
G3/09 50397

Translation of "Preobrazovatel' chastoty na volnu 2,2mm", Academy of Sciences USSR, Institute of Space Studies, Preprint 166, Moscow, 1974, 16pp.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546 OCTOBER 1974

STANDARD TITLE PAGE

1. Report No. NASA TT F-15,964	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle 2.2 mm WAVELENGTH FREQUENCY CONVERTER		5. Report Date October 1974 6. Performing Organization Code
7. Author(s) Yu. B. Khapin		8. Performing Organization Report No. 10. Work Unit No.
9. Performing Organization Name and Address SCITRAN Box 5456 Santa Barbara, CA 93108		11. Contract or Grant No. NASw-2483 13. Type of Report and Period Covered Translation
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Translation of "Preobrazovatel' chastoty na volnu 2,2mm", Academy of Sciences USSR, Institute of Space Studies, Preprint 166, Moscow, 1974, 16 pp.

16. Abstract

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17. Key Words (Selected by Author(s))	18. Distribution Statement
	Unclassified - Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	11	

2.2 mm WAVELENGTH FREQUENCY CONVERTER

Yu. B. Khapin

ABSTRACT. We report the results of a theoretical and experimental study of a 2.2 mm wavelength frequency converter. When using the bilinear representation of the nonlinear element, we obtain the expressions for the frequency converter transfer and impedance characteristics with account for the parasitic parameters of the nonlinear element. A 2.2 mm wavelength frequency converter was developed on the basis of the theoretical study. A Schottky barrier diode is used as the nonlinear element. The frequency converter conversion losses are 9 dB in the wideband regime. The relative noise temperature is 1.2.

Considerable progress has been made in recent years in the /3* field of signal generation in the millimeter and submillimeter wavelength band. In addition, the planar technology methods which have been developed make it possible to fabricate diode resistive structures — Schottky barrier diodes (SBD) — which compete successfully with the conventional point-contact diodes. Along with having a practically ideal volt-ampere characteristic in comparison with the point-contact diodes, the SBD also have other advantages, such as high electrical strength, stability, long life, less sensitivity to

*Numbers in the margin indicate pagination in the original foreign text.

ambient medium influence, better parameter reproducibility, and better noise characteristics. The well-known advantages of exploitation of the subject spectrum segment require comparable advances in the field of receiving system developments. In this connection, there is definite interest in development of one of the trends in RF reception technology — the development and fabrication of uncooled detector and superheterodyne devices; specifically, devices intended for measuring RF noise power in a certain frequency band, which are termed radiometers*. Detector receivers are used in those cases when the primary requirement is simplicity and compactness of the structure along with comparatively moderate sensitivity requirements. Acceptable detector temperature sensitivity is provided by the fact /4 that it is inversely proportional to the input received frequency band, which in this wavelength range reaches values which are large in absolute magnitude. There are a large number of detector designs used in detector radiometers [1, 2]. As a rule, they all use p-type tungsten-silicon point contacts as the nonlinear element. Unfortunately, while having quite high sensitivity (the equivalent noise power at 140 GHz for the best specimens is $1.6 \cdot 10^{-12}$ W · Hz$^{-1/2}$ [1]), they have poor stability and parameter reproducibility. The use of stable contacts (SBD), fabricated using planar technology, is difficult because of the necessity for applying positive bias to the nonlinear element. This leads to marked increase of the diode flicker noise.

The superheterodyne system always yields the best results in obtaining highest sensitivity. The sensitivity of the superheterodyne radiometer depends to a considerable degree on the frequency converter parameters. In turn, the transfer and impedance characteristics of millimeter and submillimeter wavelength band frequency converters are determined not only by the shape of the nonlinear element volt-ampere curve, but also by its parasitic parameters. Survey of the literature data on frequency converters for this spectrum shows that the nonlinear element parasitic parameters are not

*In the following, we shall consider only radiometric devices.

considered when examining their characteristics. The impedance characteristics are taken to be equal to those obtained from examination at low frequency, as is done in [3], for example. The conversion losses are calculated from the formula

$$L = L_0 (1 + R_s/R_b + \omega^2 C_b^2 R_b R_s),$$

where L_0 are the conversion losses determined at low frequency; R_s /5 is the diode series resistance; C_b is the barrier capacitance; R_b is the barrier resistance; ω is the working frequency. In the general case, loss calculation using this formula is not correct.

In the present paper, we examine frequency converter transfer and impedance characteristics with account for the parasitic parameters of the nonlinear element. Results are presented of an experimental study of a 2.2 mm wavelength frequency converter.

Frequency Converter Transfer and Impedance Characteristics

To obtain the frequency converter characteristics, we use the complex amplitude method. The volt-ampere characteristic of the nonlinear element (NE) can be written in general form:

$$i = f(U), \tag{1}$$

$$U = U_h \cos \omega_h t + U_1 \cos \omega_1 t, \tag{2}$$

where v_h and v_1 are the heterodyne and signal voltage amplitudes, respectively, and $v_h >> v_1$.

Converting to complex amplitudes, we represent the currents flowing in the system as follows:

$$\sum_{n=-\infty}^{\infty} \dot{I}_n \cdot e^{j\omega_n t} = \sum_{k=-\infty}^{\infty} g_k \cdot e^{j\omega_k t} \cdot \sum_{m=-\infty}^{\infty} \dot{U}_m \cdot e^{j\omega_m t}. \tag{3}$$

Here,

$$\omega_n = n\omega_h + \omega_1 = -\omega_{-n}.$$

We now assume that nonzero impedances exist in the system only at the frequencies $\omega_h + \omega_0$; ω_0 and $-\omega_h + \omega_0$, i.e., at the signal, intermediate, and mirror frequencies. Then the matrix connecting the complex current and voltage amplitudes is written as follows: /6

$$\begin{vmatrix} \dot{I}_1 \\ \dot{I}_0 \\ \dot{I}_{-1}^* \end{vmatrix} = \begin{vmatrix} g_0 & g_1 & g_2 \\ g_1 & g_0 & g_1 \\ g_2 & g_1 & g_0 \end{vmatrix} \begin{vmatrix} \dot{V}_1 \\ \dot{V}_0 \\ \dot{V}_{-1}^* \end{vmatrix} \qquad (4)$$

Thus, for the three-frequency regime case, the multifrequency frequency converter system can be reduced to an equivalent 6-pole network (Figure 1).

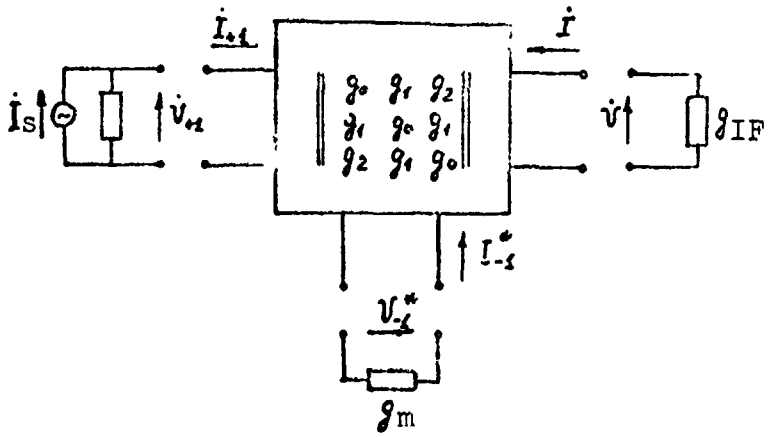


Figure 1. Frequency converter equivalent circuit

We represent the system of Equations (4) in the form:

$$\begin{vmatrix} \dot{I}_1 \\ \dot{I}_0 \\ \dot{I}_{-1}^* \end{vmatrix} = g_0 \begin{vmatrix} 1 & \mu_1 & \mu_2 \\ \mu_1 & 1 & \mu_1 \\ \mu_2 & \mu_1 & 1 \end{vmatrix} \begin{vmatrix} \dot{V}_1 \\ \dot{V}_0 \\ \dot{V}_{-1}^* \end{vmatrix} \qquad (5)$$

Here, μ_1 and μ_2 are the conductivity modulation coefficients. We see from these equations that the signal and intermediate frequency currents depend on the load at the mirror frequency.

Let us examine the case which is most interesting for the submillimeter wavelength band of equality of the load at the mirror and signal frequencies, i.e., the wide-band regime case:

$$Y_m^* = g_s. \tag{6}$$

Solving (5) with account for Condition (6), we obtain the relations for calculating the minimal conversion losses L_{min}, optimal signal-frequency conductivity $g_{s.opt}$, and output conductivity g_{out} of the frequency converter.

$$L_{min} = \alpha \frac{1+\sqrt{1-\mu^2}}{1-\sqrt{1-\mu^2}}, \tag{7}$$

$$g_{s.opt} = (g_0+g_2)\sqrt{1-\mu^2} \tag{8}$$

$$g_{out} = g_0\sqrt{1-\mu^2}, \tag{9}$$

/7

$$\mu = 2\frac{\mu_1^2}{1+\mu_2}. \tag{10}$$

Determination of NE Conductivity Modulation Coefficients

One of the most important characteristics of the NE used in millimeter and submillimeter wavelength band frequency converters is their limiting frequency:

$$\omega_{lim} = \tau^{-1} = (R_s \cdot C_b)^{-1}, \tag{11}$$

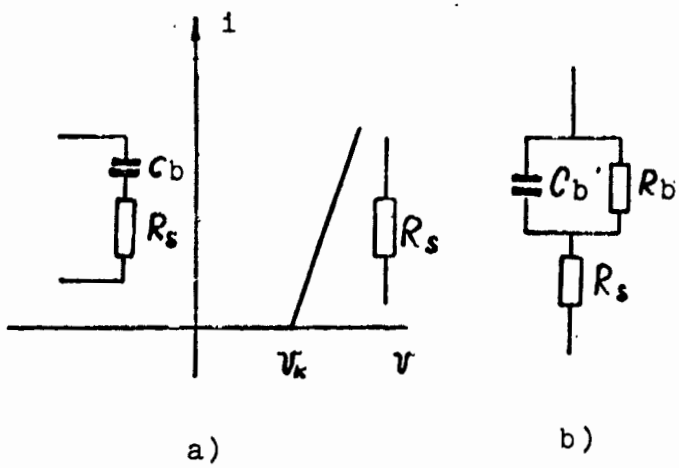
where C_b is the NE barrier capacitance with zero bias, R_s is the NE series resistance (see Figure 2b).

In order to simplify the analysis and account for parasitic parameter influence on the frequency converter primary characteristics,

we use the bilinear representation of the NE volt-ampere characteristic (Figure 2a). Then, in the voltage region $v > v_k$, the NE volt-ampere characteristic is written in the form:

$$i = g_{max} \cdot v, \qquad (12)$$

where $g_{max} = R_s^{-1}$.



a) b)

Figure 2. a) Bilinear representation of diode volt-ampere characteristic; b) equivalent diode circuit

Conductivity modulation is accomplished by the sinusoidal heterodyne voltage $v = v_h \cos \omega_h t$. Considering the NE parasitic parameter influence, we expand the conductivity into a Fourier series and determine the NE modulation coefficients and the Fourier series coefficients g_0; g_1; g_2 ... g_n:

$$\mu_n = \frac{g_n}{g} = \frac{\sin n\theta}{n\pi\left[\theta/\pi + \left(\frac{\omega}{\omega_{lim}}\right)^2\right]} \qquad (13)$$

$$\hat{g}_0 = \frac{\theta/\pi + (\omega/\omega_{lim})^2}{1 + (\omega/\omega_{lim})^2}, \qquad (14)$$

/8

$$\hat{g}_n = \frac{\sin n\theta}{n\pi} \cdot \frac{1}{1 + (\omega/\omega_{lim})^2} \qquad (15)$$

where ω is the working frequency, θ is the optimal heterodyne voltage reference angle, $n = 1, 2, 3, \ldots$, $\hat{g}_0$ and $\hat{g}_n$ are the normed conductivities $\hat{g}_0 = g_0/g_{max}$, $\hat{g}_n = g_n/g_{max}$.

Computer calculations were made using (7) - (9) and (13) - (15), and curves (Figure 3) were plotted of the frequency converter minimal conversion losses, optimal signal-frequency conductivity and output conductivity (Figure 4) as functions of the ratio ω/ω_{lim}.

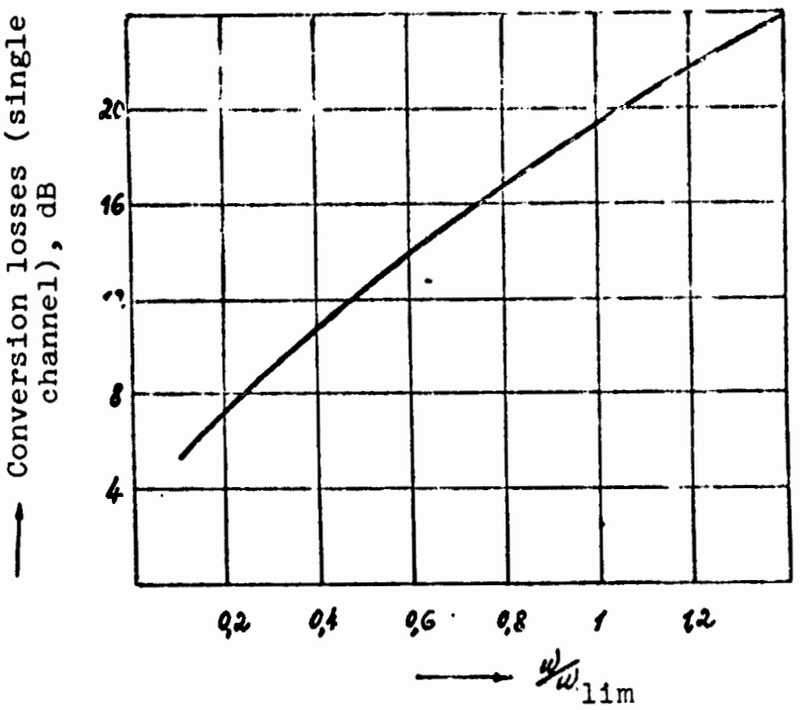


Figure 3. Conversion loss versus ratio ω/ω_{lim} (wide-band regime)

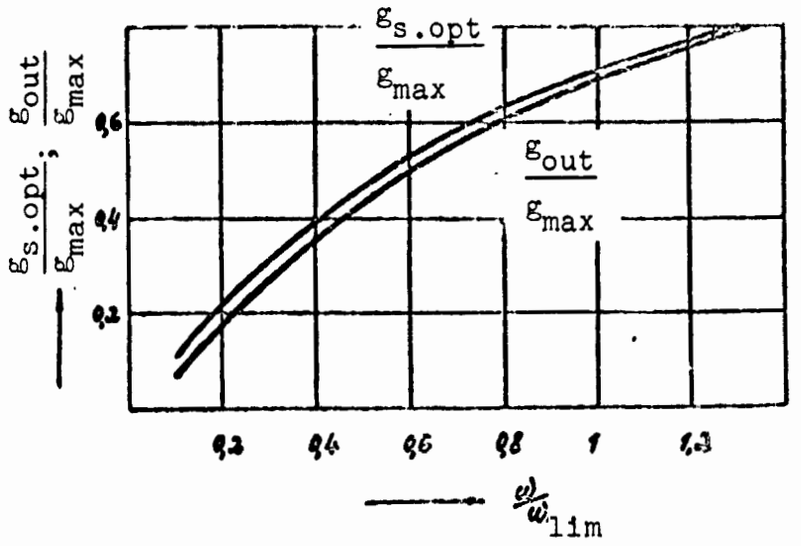


Figure 4. Normed signal generator conductivity and normed frequency converter output conductivity versus ω/ω_{lim}

Results of Experimental Stuay

Schottky barrier diodes are presently used [4 - 6] in millimeter wavelength frequency converters, and provide stable and reproducible contact. In the present study, as in [4], we used a Ga As Schottky barrier diode.

From SHF measurements, the diode time constant is $\tau = 0.4$ nsec ($C_b = 0.04$ pF, $R_s = 10$ Ohm).

A 2.2 mm wavelength frequency converter, shown in cross section in Figure 5, was constructed on the basis of the above theoretical study. The diode is positioned in the 0.8 x 1.6 mm^2 waveguide input section. It is formed by advancing the pin with structure bonded to it until it touches the whisker. The whisker is phosphor bronze. The frequency converter output is made in the form of a 50 Ohm impedance coaxial line. With diode time constant 0.4 nsec, the frequency converter input and output impedances are 30 and 35 Ohm, respectively. The low output impedance made it possible to obtain wideband output without using an impedance transformer. Decoupling of the signal and intermediate frequencies is accomplished by the structure capacitance.

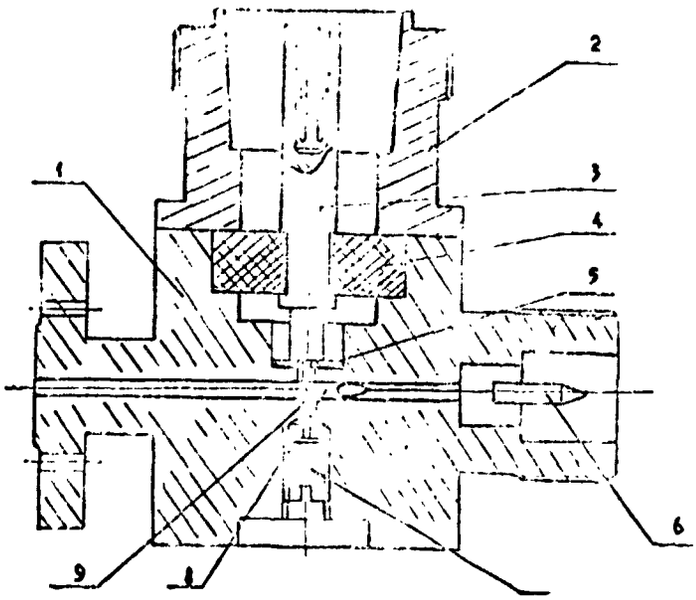


Figure 5. 2.2 mm wavelength frequency converter:

1 — case; 2 — output connector; 3 — holder with contact needle; 4 — support washer; 5 — spacer; 6 — short; 7 — pin; 8 — 0.8 x 1.6 mm^2 waveguide input section; 9 — semiconductor structure

This design makes it possible to obtain conversion losses of 9 dB in the wide-band regime. This includes the circuit losses which are estimated to be about 0.8 to 1 dB. The frequency converter relative noise temperature is 1.2. For the NE with time constant 0.4 nsec, the calculated conversion losses, found from Figure 3, are 8 dB in the wide-band regime, which is in good agreement with experiment.

The conversion losses of the frequency converter described above exceed those we obtained earlier [4] by 4 dB. The use of diodes with shorter time constant will make it possible to reduce the conversion losses.

In conclusion, the author wishes to thank V. S. Etkin and I. A. Strukov for their continued interest and assistance in this study.

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